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Cryogenic Neutron Spectrometer Development

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Cryogenic microcalorimeter detectors operating at temperatures around ~ 0.1 K have been developed for the last two decades, driven mostly by the need for ultra-high energy resolution ($< 0.1\%$) in X-ray astrophysics and dark matter searches [1]. The Advanced Detector Group at Lawrence Livermore National Laboratory has developed different cryogenic detector technologies for applications ranging from X-ray astrophysics to nuclear science and non-proliferation. In particular, we have adapted cryogenic detector technologies for ultra-high energy resolution gamma-spectroscopy [2] and, more recently, fast-neutron spectroscopy [3].

Microcalorimeters are essentially ultra-sensitive thermometers that measure the energy of the radiation from the increase in temperature upon absorption. They consist of a sensitive superconducting thermometer operated at the transition between its superconducting and its normal state, where its resistance changes very rapidly with temperature such that even the minute energies deposited by single radiation quanta are sufficient to be detectable with high precision.

The energy resolution of microcalorimeters is fundamentally limited by thermal fluctuations to $\Delta E_{\text{FWHM}} \approx 2.355 (k_B T^2 C_{\text{abs}})^{1/2}$, and thus allows an energy below 1 keV for neutron spectrometers for an operating temperature of $T \approx 0.1$ K. The ΔE_{FWHM} does not depend on the energy of the incident photon or particle. This expression is equivalent to the familiar $(F \epsilon E_\gamma)^{1/2}$ considering that an absorber at temperature T contains a total energy $C_{\text{abs}} T$, and the associated fluctuation are due to variations in uncorrelated ($F=1$) phonons ($\epsilon = k_B T$) dominated by the background energy $C_{\text{abs}} T \gg E_\gamma$.

The rationale behind developing a cryogenic neutron spectrometer is the very high energy resolution combined with the high efficiency. Additionally, the response function is simple and the instrument is transportable. We are currently developing a fast neutron spectrometer with 0.1% energy resolution at 1 MeV neutron energy with an efficiency of $> 1\%$. Our fast-neutron spectrometers use boron-based and ^6LiF absorber crystals with Mo/Cu thermistors readout. They have achieved an energy resolution of 5.5 keV FWHM for 2.79 MeV deposited in ^{10}B by thermal neutron capture (fig. 1), and 46 keV FWHM for fast (MeV) neutrons absorbed in ^6LiF (fig. 2). Since the energy resolution does not depend on the neutron energy, we expect a similar energy resolution for MeV neutron energies. The response function is given simply by the cross section of the capture reaction, offset from zero by the Q -value of the capture reaction. This allows straightforward discrimination against gamma-events, most of which deposit less than $Q_{^6\text{Li}} = 4.79$ MeV in the ^6LiF absorber, and easy deconvolution of the neutron spectrum,

since there is only a single capture reaction in ${}^6\text{Li}$ and the spectrum is not affected by edge effects or geometric broadening.

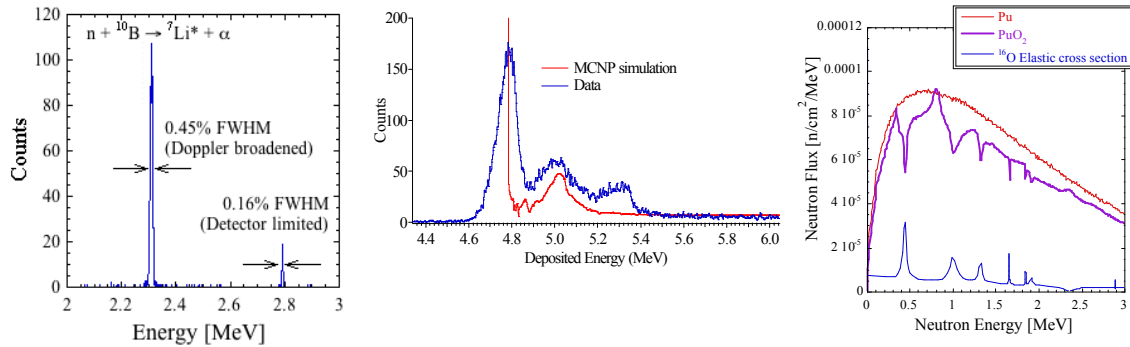


Fig 1 (left): Thermal neutron spectrum from a cryogenic spectrometer with a TiB_3 absorber. The two peaks correspond to two different capture reactions in ${}^{10}\text{B}$. The energy resolution of ~ 5 keV is sufficient to show the 10.5 keV Doppler-broadening due to the finite life time of the first excited state in ${}^7\text{Li}^*$.

Fig 2 (center): Fast-neutron spectrum from weak ${}^{252}\text{Cf}$ and ${}^{210}\text{Po}$ sources with 46 keV FWHM resolution using a 94% enriched ${}^6\text{LiF}$ absorber crystal. The broad peak, shifted by $Q = 4.79$ MeV to ~ 5 MeV is due to increased absorption by ${}^6\text{Li}$ at 0.25 MeV. The alpha peak at ~ 5.3 MeV is due to ${}^{210}\text{Po}$. In red is the expected spectrum of a ${}^{252}\text{Cf}$ source simulated with MCNP, not taking into account the alpha source.

Fig 3 (right): MCNP simulation of the neutron spectrum of a Pu and a PuO_2 source for a spectrometer resolution of 10 keV. Neutron microcalorimeter arrays will allow the detection of light elements in a heavy-element matrix from spectral features at nuclear resonance energies, even through thick shielding.

The current challenge for microcalorimeters is their necessarily small effective pixel area, $\sim 1\text{cm}^3$ for neutron spectrometer pixels, and their slow decay time, $\sim 10\text{ms}$ for neutron spectrometers. The pixel size is limited by the requirement for low C_{abs} for high energy resolution; the decay time is set by the intrinsically weak thermal coupling between materials at low temperatures. Both issues can be addressed by fabricating large detector arrays. This will enable high-precision neutron spectrometry with high statistics, such as simulated for Pu analysis in fig 3.

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